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OCEAN GEOID DETERMINATION INVESTIGATION

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INVESTIGATION

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1. SCIENTIFIC/TECHNOLOGICAL DESCRIPTION OF THE INVESTIGATION

The outstanding feature of the GEOS-C mission from the standpoint of Ocean Geoid Determination is the fact that it provides the prospect of conducting two independent kinds of experiments to determine the ocean geoid with a spatial resolution of about five degrees. These are the experiments based on the altimeter and the satellite-to-satellite tracking systems. Each of these approaches is, by itself, entirely new and hence provides an independent check of existing information. The primary GEOS-C Ocean Geoid Determination Investigation, therefore, is the combined investigation of the mean sea level geopotential surface by means of the altimeter and the satellite-to-satellite tracking system.

The altimeter data, when calibrated and corrected, e.g., for sea state and other effects, constitute measures of the distance between the GEOS-C spacecraft and the ocean surface. Knowledge of the satellite altitude relative to a reference ellipsoid and knowledge of the oceanographic departures of the sea surface topography from the geoid will then permit the determination of the geoid. The chief problem is expected to be the determination of the satellite orbital altitude. The primary tracking tools for doing this are the statellite-to-satellite tracking system and precision lasers. Data from these systems and the others tracking GEOS-C, including C-Band radars, USB range and range rate stations and Tranet Doppler stations, will be used to find the satellite height.

The satellite-to-satellite tracking system itself can sense the gravity field accelerations directly by observing the perturbing effects on the velocity and position of GEOS-C. The investigation based on tracking between GEOS-C and ATS-F is analogous to the one which has already been used to discover the lunar mascons by tracking lunar orbiters from earth. The spatial resolution of this approach is a function of the satellite altitude. It is estimated to be of the order of five degrees in the case of GEOS-C. The altimeter footprint diameter is of the order of a tenth of a degree, geocentric, hence its spatial resolution along the satellite track can, in principle, be of the order of a degree or less.

Thus the altimeter and satellite-to-satellite tracking approaches can, from the scientific standpoint, be used to conduct an ocean geoid determination investigation at the 5° spatial resolution level. Preliminary estimates indicate that both methods should be capable of height resolution of the order of five meters. The experiment using the two systems, the altimeter and the satellite-to-satellite tracking system, but aimed at the single objective of the determination of the ocean geoid, accordingly affords an exceptional opportunity for ocean geoid determination research.

This single scientific experiment will be proposed in terms of a combination of two investigations in order to conform to the investigation categories specified in the Proposal Briefing Information Handbook (ref. 1). These are an Ocean Geoid Determination Investigation, based primarily on altimeter sensing and orbital altitudes determined with the aid of satellite-to-satellite tracking data, and a Gravity Model Improvement Investigation based also on the use of satellite-to-satellite tracking data for sensing the gravity field directly.

The data requirements, theoretical formulation, computer program development, and preprocessing costs of the Ocean Geoid Determination Investigation should, with little or no additions, suffice for the companion Gravity Model Improvement Investigation. The actual analysis of the combination of altimeter and satellite-to-satellite tracking data and related information to determine the gravity field and geoid may involve a modest additional cost beyond that of an Ocean Geoid Determination Investigation of the type indicated in reference 1. A Gravity Model Improvement Investigation of this type is accordingly proposed here as the second part of the combined proposal.

The preceding discussion is included for convenience in both proposals and in order to indicate the fact that they constitute a combined set of investigation proposals for conducting what can be thought of as a single experiment. Each proposal will, as indicated, stress certain particular aspects of the overall combined experiment.

2. BACKGROUND

Satellite contributions to the determination of the current ocean geoid have spatial resolutions corresponding to half-wavelengths of about 18° (4, 7). Surface gravimetry achieves representations with finer resolution, in the 1° to 5° range, however it covers only about half the ocean surface. Precisions of the order of five meters are obtained (4, 14, 19, 22). The GEOS-C altimeter and satellite-to-satellite tracking systems, which are expected to yield comparable results, will fill in the gaps and provide valuable independent knowledge where data now exist.

The value of satellite altimetry and satellite-to-satellite tracking in this connection has been pointed out by Kaula, Von Arx and their colleagues (19).

The ATS-F/GEOS-C satellite-to-satellite tracking experiment was first proposed in 1969 (23).

3. OBJECTIVES

The general objective of the proposed GEOS-C Ocean Geoid Investigation is to determine the ocean geoid over extended areas with a space resolution corresponding approximately to five degree squares and a height resolution of the order of five meters using the data from GEOS-C and other related information which has become available in connection with the National Geodetic Satellite Program (NGSP). Smaller features corresponding to squares of the order of 1° on a side will also be studied in selected regions.

A short term objective is to use GEOS-C data to determine the geoid with resolutions in the one to five degree range in the western North Atlantic and other ocean areas viewed by ATS in its western hemisphere location over 94°west longitude, and in the remaining areas of the world's oceans as the data sets make this possible.

A longer term objective, associated with the second year of operation of GEOS-C, is to refine the definition of the ocean geoid in the one to five degree range in the regions viewed by ATS in its eastern hemisphere location at 35° east longitude. A second long term objective is to improve the knowledge of the ocean geoid by utilizing the new information expected to become available from the first year of analysis of GEOS-C data and from other contemporary studies relating to aspects of the investigation such as those involving satellite orbit determination, tides, ocean currents, circulations, and quasi-stationary departures from the marine geoid.

The results generated through the achievement of these objectives will serve as foundations for the more advanced missions and experiments of similar types which are contemplated as part of the emerging Earth and Ocean Physics Applications Program (EOPAP). (2) In particular they will provide the first actual experience with the ocean geoid determination experiment envisioned for Seasat I and Seasat II in which the goals are to determine the ocean geoid with accuracies of the order of a meter and a decimeter, respectively.

The principal challenge in connection with determining the ocean geoid is expected to be that of determining the GEOS-C satellite orbital altitude in appropriate reference systems associated with the earth's center and with local geodetic features such as geoid locations at landfalls, for example. Accordingly, the acquisition of altimeter data should always be accompanied by the acquisition of suitable sets of tracking data, including, in particular, satellite-to-satellite tracking data and precise, i.e., 10-cm, laser tracking data. This means, for example, that each pass of altimeter data involving passage under GEOS-C within about 60° of the ATS-F subpoint should be accompanied by satellite-to-satellite tracking data throughout that pass, consisting of about half a revolution of GEOS-C, and an adjacent pass, i.e., the one immediately preceding or following it. In addition, laser and other tracking data having equivalent accuracy of about a meter or better, including, e.g., Tranet Doppler data, should be taken during every tracking pass opportunity in a two-revolution interval centered on the mid-time of the altimeter pass. Altimeter data taken in a pass going through the immediate neighborhood of the GEOS-C calibration area outlined by the stations at Goddard, Wallops Island, Boston, Bermuda, Antigua, Canal Zone, and Cape Kennedy, should be accompanied, in particular, by tracking from all lasers in that neighborhood having 10-centimeter accuracy as well as tracking from all other tracking systems in that area in the manner specified above.

Wherever 10 cm lasers are collocated with C-Band radars, which is expected to occur at Wallops, Bermuda, Cape Kennedy, Grand Turk, and/or Antigua, for example, both systems should track throughout the entire pass above about 5° elevation angle if the visibility during any part of the pass permits laser tracking.

A representative set of altimeter observing intervals should permit the gathering of information about sea state possibly through alternating between the long and short pulse altimeter operating modes during a given pass.

In order to appropriately exploit the spatial resolution capability of the altimeter system it will be important to obtain altimeter data from tracks which are separated by about 5° (the estimated daily spacing) and 1° - 2° (the estimated spacing over longer intervals). Observations should be taken during such sets of intervals in both directions (i.e. north-south and south-north) over a given region of interest. The 1° - 2° patterns should be generated whenever primary tracking, i.e., 3 or more 10 cm lasers and satellite-to-satellite tracking, is available, e.g., in the western North Atlantic calibration area. The 5° patterns should be developed over the remainder of the oceans to the greatest extent practicable.

The justification of the objectives can be indicated in terms of the fact that the investigation will provide a representation of the ocean geoid on the basis of a relatively homogeneous set of data taken in a relatively short time period, i.e. about a year. These data and the determinations based on them will provide knowledge of the ocean geoid in regions where little or nothing is now known about it, and they will also constitute a completely independent determination of the ocean geoid in regions where information now exists. Current knowledge is based on data taken from a great number of instruments and systems of several different types over periods of many years. The current knowledge can thus be viewed as being based on a patchwork of partial data sets of varying accuracies. The relatively unified, homogeneous picture that should emerge from a single altimeter and observing system involving a single satellite-to-satellite tracking system in a relatively short period of time should be of great value in giving a better picture of the ocean geoid on a global basis.

4. APPROACH

The investigation will utilize altimeter data and other data from GEOS-C to determine the geometry of the ocean geoid. The altimeter will yield data which, when appropriately calibrated and corrected, will constitute measures of the distances between the GEOS-C spacecraft and the topography of the sea surface. Determination of the geoid geometry involves the use of knowledge about the departures of the sea surface from the geoid and information concerning orbital altitudes of the GEOS-C spacecraft in a common reference system such as one associated with the earth's center of mass or a reference ellipsoid. Those factors which affect the interpretation of the GEOS-C altimeter data in terms of the geometry of mean sea level are listed in Table I.

Table I

Factors Affecting Interpretation of GEOS-C Altimeter Data in Terms of the Geometry of Mean Sea Level

A. Instrumental Altimeter Errors
   i. Global altimetry
   ii. Localized altimetry
B. Orbital Altitude of GEOS-C in reference system associated with:
   i. The earth's center of mass
   ii. Local tracking station configurations
C. Sea State and Wave Height Effects on Altimeter Signals
D. Departures of the Sea Surface Topography from the geoid due to:
   i. Tides
   ii. Currents and circulations
   iii. Wind set-up

The general concept of the investigation is to make use of all available information about these effects and, as appropriate, to generate in the course of the investigation more refined information about some of them. In particular, it is planned as part of this investigation to devote special effort to the accurate determination of the orbital altitude and, as circumstances appear to warrant, the determination of altimeter instrument biases.

Uncertainties associated with the factors indicated in Table I are estimated to be of two types. Those associated with items C and D, i.e., the oceanographic factors, will probably be of the order of a meter or less all told in most ocean areas. Those associated with the first two items maybe significantly larger. Two meters is called for as the altimeter instrument error in the global mode. The satellite orbital altitude error may be still larger, of the order of two to four meters over large areas of the oceans. Accuracies appear to be improving recently by a factor of the order of two or three each four or five years. (Cf., e.g., ref. 44.) It appears from some of the results indicated there and more recent findings that a five meter altitude goal should be achievable in the GEOS-C time period with the aid of satellite-to-satellite tracking data and precise laser observations. The half meter error of the altimeter instrument in the localized altimetry mode is probably reasonably well matched to the accuracy of the local relative altitude which can be derived from 3 or more 10 cm lasers.

It is anticipated that information about the effects of all four categories listed in Table I will be generated in the course of the GEOS-C Project activities and investigations. It is planned to utilize whatever information of this type becomes available in time to be of significant use in this investigation. In this connection it is planned to work closely with those selected for investigations concerning intercomparisons, orbit determination improvement, sea state and wave analysis, ocean tides, and quasi-stationary departures from the ocean geoid in connection with the corresponding items listed in Table I. Such co-operative endeavors are already specifically planned in connection with the GSFC proposals which are being submitted concurrently in these areas.

Specific present plans for representing and/or determining effects listed in Table I are as follows:

A. Instrumental Altitude Errors

Experiments will be conducted within this investigation to determine whether meaningful results are obtained by solving simultaneously for biases and parameters representing the ocean geoid and possibly other oceanographic parameters. Instrument biases found by the calibration activity and which may become available from the Intercomparison investigation will be also utilized. Problems associated with format and related matters will continue to be worked out together with those concerned with these activities.

B. Orbital Altitude of the GEOS-C Spacecraft

The principal problem in the determination of the ocean geoid will probably be the determination of the orbital altitude of the GEOS-C spacecraft with respect to a reference system associated with the earth's center of mass or a reference ellipsoid. It is planned to devote a major part of the investigative effort to the solution of this problem. This problem will be attacked in the following ways.

Firstly, the best available geopotential models and tracking station coordinates will be employed in the studies. These will be of two types. First there will be those derived from pre-GEOS-C analyses, primarily those results generated in connection with the National Geodetic Satellite Program (NGSP) such as, for example, those in the GEM series, dynamical determinations of tracking station coordinates, short arc studies, as well as the results generated at the Smithsonian Astrophysical Observatory, the Ohio State University, and the National Geodetic Survey of the National Oceanic and Atmospheric Administration (NOAA). (3-7, 17). New information generated in connection with this investigation and other GEOS-C investigations, in particular those having to do with gravity model improvement and tracking station location improvement, will also be utilized in this investigation to the extent that it becomes available in time for this purpose.

Three new types of tracking data will be available from GEOS-C for precise orbit determination. These are satellite-to-satellite tracking data, precise laser tracking data, and data from the altimeter itself. In addition, there will be the more traditional types of data, i.e., from the C-band radars, the Tranet Doppler system, and the USB Goddard ground stations. All available tracking data will be employed in the effort to derive the best information about the GEOS-C orbital altitude, and to permit the most realistic estimates of the associated uncertainties. In particular, the laser tracking data of ten-centimeter accuracy obtained from stations such as Goddard, Wallops, Merritt Island, Bermuda, Antigua, and/or Grand Turk should permit determination of the GEOS-C altitude relative to the triangles associated with these stations to better than a meter. The GEOS-C/ATS satellite-to-satellite tracking data, good to 0.08 cm per second, are expected to extend the region in which the altitude uncertainty is no larger than about 2 to 4 meters to encompass large portions of the Pacific and Atlantic Oceans viewed by ATS-F. Simulation studies dealing with this have been conducted and will be continued in order to help find the best data taking patterns and analytical approaches. Determination of the GEOS-C orbital altitude over the rest of the globe will depend also upon data from precise tracking system involving C-band radars, Tranet Doppler stations and lasers of intermediate accuracy (i.e., a meter or two), located outside the western North Atlantic calibration area such as those operated by the SAO, for example. The determination of orbital altitude has been and is being studied by means of simulations.

Methods and techniques for combining and weighting data which have been worked out and tested over the years in connection with precision orbit determination and geopotential and tracking station location studies will be employed. (3-6, 17, 18)

C. Sea State and Wave Height Effects

It is planned to carry out the appropriate coordination involving format and similar considerations together with the Principal Investigator for sea state and wave analysis.

D. Departures of the Sea Surface Topography from the Ocean Geoid

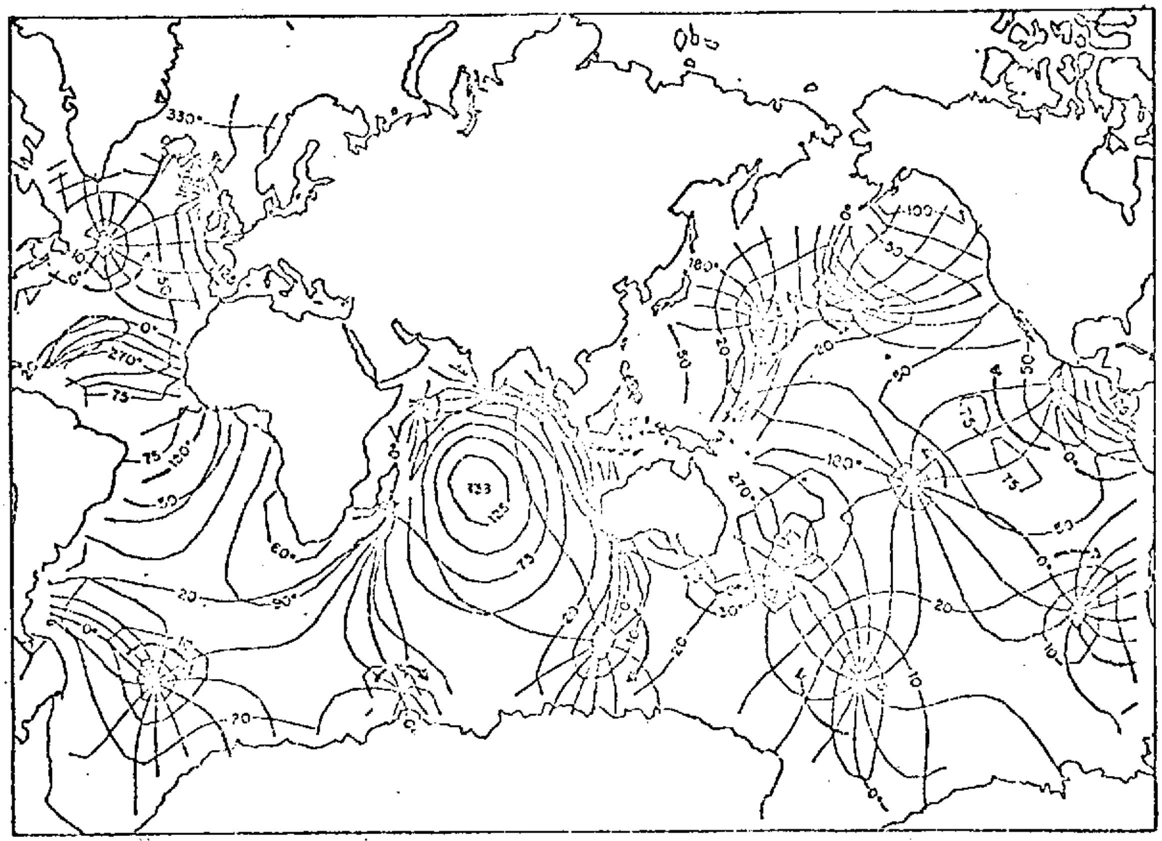
i. Tides

Tides will be modelled with the aid of theoretical methods employed by Hendershott. (Cf. for example, references 8 and 37.) A typical tidal representation presented by Hendershott and Munk is seen in Figure 1. Hendershott's researches are generating additional models of this type. It is anticipated that more advanced versions may become available in the GEOS-C time period. Hendershott has suggested in discussions that the representation of the ref. cited above will be an appropriate and convenient one for use in studies of this type. (9) Accordingly, it is planned to implement such a formulation in the ocean geoid analysis computer program system. As was indicated above, it is estimated that uncertainties associated with such a model for the ocean tides will be no more than about a meter over most of the ocean areas.

ii. Currents and Circulations

A representation of the dynamic topography, or quasistationary departure of the sea surface from the geoid, has been presented by Stommel. (10) It appears in Figure 2. It is planned to include such a representation in the ocean geoid analysis computer program system. This will be done by specifying values at points of an appropriately spaced mesh and interpolating to determine values at other points.

Numerical mathematical models of ocean current systems have been developed in the course of researches of Professors Bryan and Holland (11, 12). It is planned to continue the discussions with them and, as appropriate, to include representations of models of the types which they make available in the ocean geoid analysis computer program system.

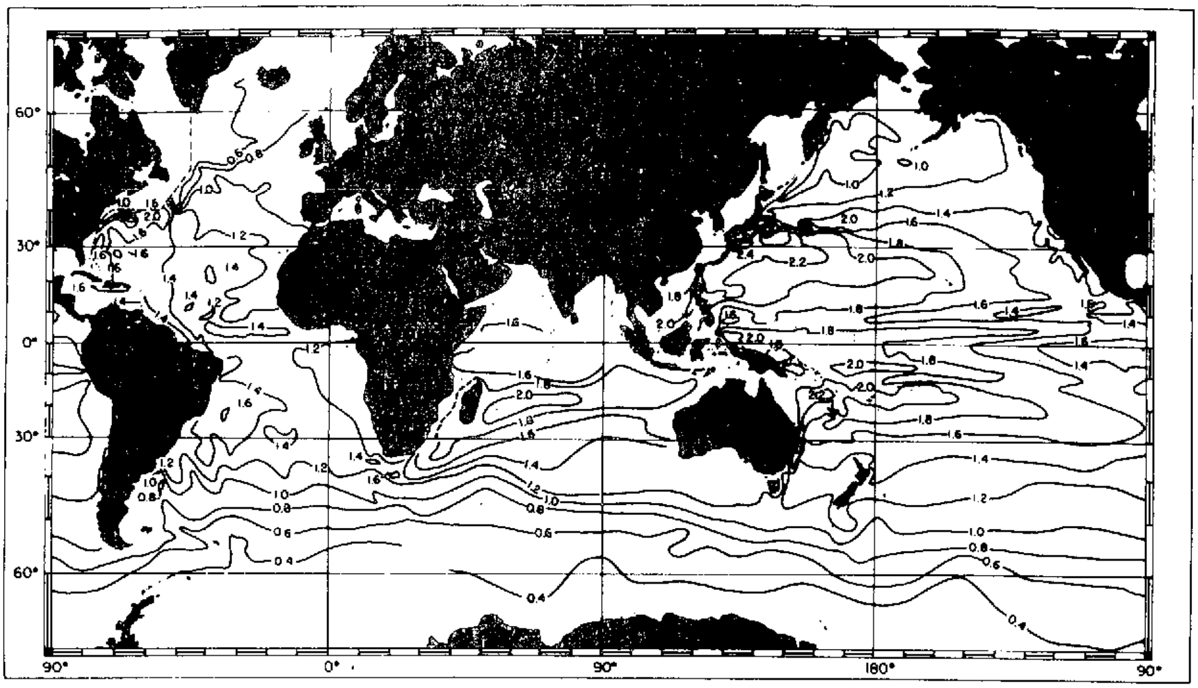


Cotidal and corange lines for the M_2 tide obtained by solving LTE with coastal values specified. Cotidal lines radiate from amphidromic points, corresponding to the progression of tidal crests in the sense indicated by the heavy arrows around these points of vanishing tidal range. High tide occurs along the cotidal lines labeled 0° just as the moon passes over Greenwich meridian. Successive cotidal lines delineate tidal crests at lunar hourly intervals. (For clarity, only selected cotidal lines are labeled, 30° corresponds to a delay of one lunar hour.) Corange lines (5, 10, 20, 50, 75, 100, 125 cm) connect locations of equal tidal amplitude (not double amplitude). They surround amphidromic points (where range vanishes and phases vary rapidly) and range maxima (where range is largest and phases nearly constant).

Figure 1

iii. Wind Setup

Similarly, effects associated with wind setup considered by other investigators will also be represented in the analyses as appropriate as they become available (13).



Dynamic Topography of the Sea Surface

Figure 2

A key feature of the investigation will be the comparison of the ocean geoid geometries obtained from GEOS-C data with those derived on the basis of previous satellite and surface gravimetric studies. The available satellite tracking data and much of the accessible surface gravity data are being used in the GEM gravity model and geoid studies presently being conducted at the GSFC by Lerch, et al, and Marsh, et al. (4, 5). Combinations of satellite gravity field information giving the features of long wavelength, of the order of eighteen degrees, and surface gravimetry giving features in the 1° to 5° range have been constructed. A number of significant results which furnish excellent starting points for this investigation have already been obtained (3-7, 14). In particular, the detailed gravimetric geoid encompassing the North Atlantic area is expected to be especially important in this connection (14). Independent comparisons with astrogeodetic data in the United States indicate that the detailed gravimetric geoid accuracies are of the order of a couple of meters (14, 20, 21). It is planned to continue these studies to refine, to the greatest practicable extent, our knowledge of the GEOS-C calibration region whose core is outlined by the stations at Goddard, Bermuda, Antigua and Cape Kennedy. Specific studies planned are to refine the detail of the geoid representation to the 10' level of spatial resolution and to vary the region over which effects of the surface gravimetry data are represented at a given point up to 20° from the present

10°. (15) Additional data to become available before the launching of GEOS-C will be incorporated in these analyses in order to obtain the best available reference geoid in the GEOS-C calibration area.

A theoretical analysis of the downward continuation of gravity from satellite altitudes to the ocean surface is already being conducted at the Woods Hole Oceanographic Institution under a contractual arrangement with the GSFC. Results of this research will be especially valuable in defining the accuracy of the pre GEOS-C satellite contributions to our knowledge of ocean geoid. Specific studies are already underway to shed light on key aspects of the ocean geoid investigation. For example, the contributions of all significant gravity terms are being estimated on the basis of Kaula's theory in terms of frequency contributions. The results will furnish valuable guides in connection with the problem of interpreting the frequency spectrum of the altimeter data in terms of ocean geoid undulations and separating them from altimeter spacecraft motions (16).

The computer program systems to be used in this investigation will include the GEODYN program, appropriately modified to permit the determination of new types of geoid parameters from altimeter and satellite-to-satellite tracking data from GEOS-C. This program system using numerical integration has already been used very extensively to determine geopotential models and tracking station locations (4).

5. DATA REQUIREMENTS

The data requirements have been discussed above, particularly in Section 4. The requirements are reviewed and summarized here. Geographical areas of interest are indicated in Table II in order of priority.

Table II

A. GEOS-C Calibration Area - outlined by Goddard, Boston, Bermuda, Antigua, Canal Zone, Cape Kennedy.

B. The Remainder of the North Atlantic Ocean

C. The Eastern Pacific Ocean Areas Viewed by ATS-F at 94°W.

D. All Other Ocean Areas Viewed by GEOS-C

E. The South Atlantic Ocean Areas Viewed by ATS-F While Drifting Between 94°W and 35°E.

F. The Indian Ocean Areas Viewed by ATS-F at 35°E.

Data should be taken in these regions in accordance with the following procedures.

Altimeter data passes should be scheduled so as to build up grids of tracks 5° apart in both the south-north and north-south directions in all the areas of Table II. The altimeter should take data at 1 second intervals.

Altimeter passes should be scheduled so as to build up, as feasible, grids of tracks 1° apart in both the south-north and north-south directions in the GEOS-C calibration area, i.e., region A of Table II.

Each altimeter track passing within 60° of the ATS-F subpoint should be tracked from ATS-F throughout a revolution pass and one immediately preceding or following it. Every SST pass should span the entire period of continuous visibility from ATS-F in a given revolution. The range rate integration interval should be 10 seconds. Range data should be taken at least once each 5 minutes at 1 second intervals for at least 20 seconds.

Each altimeter data pass should be accompanied by ground tracking, during a two revolution interval centered in the mid-time of the altimeter pass, from all laser and Tranet Doppler stations and as power permits, all C-band and USB stations whenever GEOS-C is above 5° elevation. Laser data should be taken at 1 second intervals or the shortest convenient interval, which ever is longer. Tranet data should be taken at the shortest convenient interval. C-band and USB data should be at intervals of about 6 -10 seconds, or as power resources permit. Altimeter passes in the GEOS-C calibration area should be tracked by both lasers and collocated C-band radars throughout each pass whenever laser visibility occurs in any part of the pass.

The tracking of the ATS spacecraft by its own independent tracking system should be done in conjunction with satellite-to-satellite tracking. These data are important since they will help in distinguishing between effects of ATS and GEOS motions on the satellite-to-satellite tracking data. The frequency contents of the ATS and GEOS orbital perturbations are, fortunately, quite different. Nevertheless, ATS tracking data are expected to be of good use in sorting out what is actually going on as the first attempts are made to extract information from satellite-to-satellite tracking data.

It is requested that all data formats to be used be specified as far in advance of the launch as is practicable.

6. DATA HANDLING PLAN

The data handling plan is outlined in Figure 3 which is consistent with the terminology and time schedules of appendix B of reference 1.

OCEAN GEOID DETERMINATION INVESTIGATION
DATA HANDLING FLOW CHART

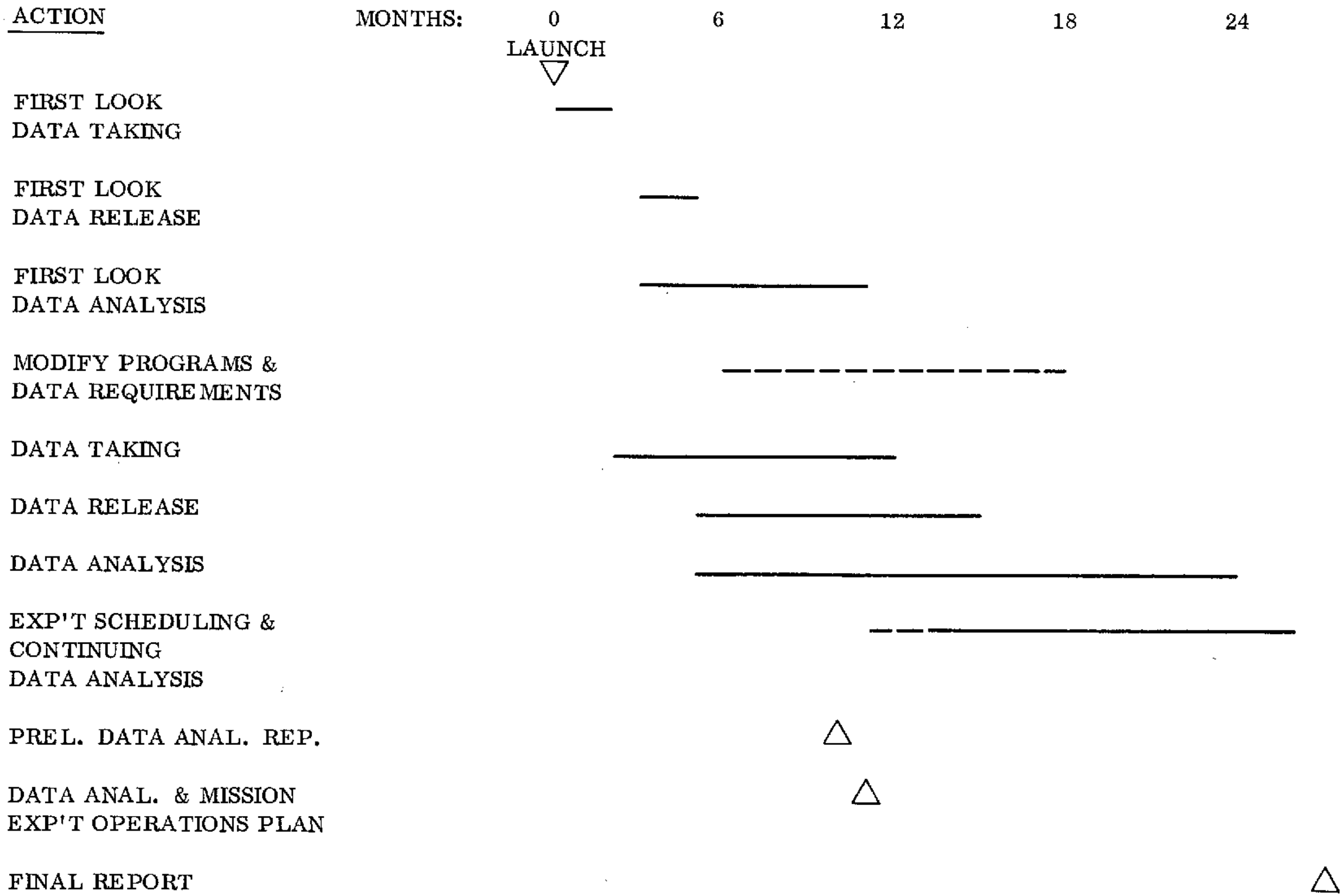


Figure 3

The deliverable data products will consist of geoid profiles and geoid maps. Geoid profiles will be based on the data from individual altimeter tracks which are isolated from one another in terms of spacing and hence do not collectively map a 2-dimensional region. Geoid maps will be based on sets of altimeter tracks which are nearly evenly spaced, e.g., at 5° intervals, and in sequences which are uninterrupted or nearly so. The "First Look" Data Analysis phase of ref. 1 is expected to yield geoid profiles. It is anticipated that geoid maps will begin to become available in a later phase on the basis of data obtained from the first half year of operation of GEOS-C.

In order to permit correlation with results of analysis of other types of data, the computer program system will be provided with the capability for solving for parameters associated with surface density distributions, free air gravity anomalies, mass points, and the sampling functions proposed by Giacaglia and Lundquist. (35) The preprocessors will be equipped to handle all appropriate correlative and housekeeping data associated with the satellite, e.g., its attitude, the tracking systems, e.g., offsets, and the environment, e.g., meteorological quantities. (34) The analysis will be conducted with the aid of the GEODYN program which is being appropriately modified to conduct analyses using altimeter and satellite-to-satellite tracking data and to incorporate the features just mentioned. The GSFC IBM 360/95 and 360/75 computers will be used. The geoid profiles and maps will be furnished on magnetic tape in formats which, it is anticipated, will specify the geoid height in meters as functions of geographic latitude and longitude. The profiles will be in the form of linear arrays, corresponding to the orbit tracks. The maps will be in the form of two-dimensional arrays.

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